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The Spatial Variation and Routine Sampling of Spawning Gravels in Small Coastal Streams

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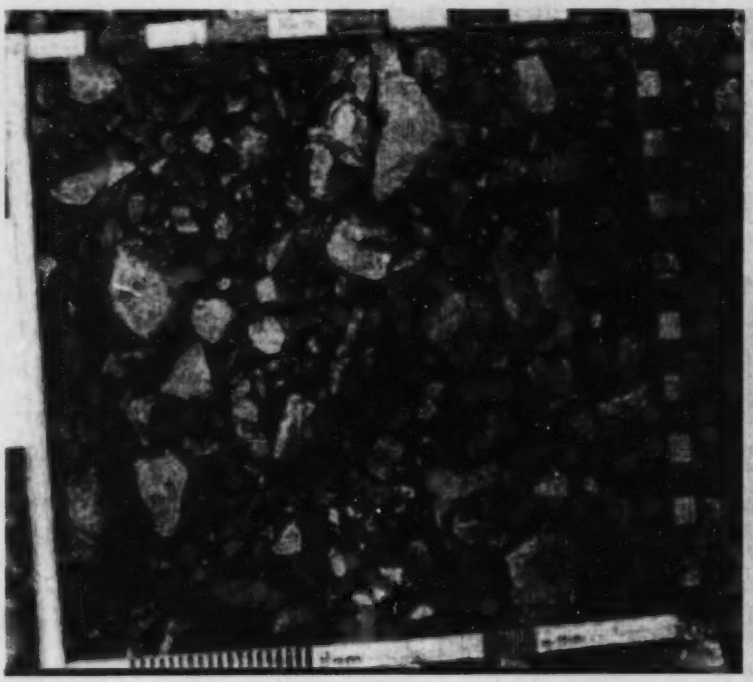

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The Spatial Variation and Routine Sampling of Spawning Gravels in Small Coastal Streams

Stephen Rice

Province of British Columbia
Ministry of Forests Research Program

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ABSTRACT

The size distribution of the sediments in the bed of a stream channel is a significant characteristic of fish habitat. Spawning gravels are sampled during habitat assessments and monitoring programs. Within a given stream, effective, representative sampling requires a clear understanding of the spatial variation of spawning gravel characteristics. This study documents and explains the spatial variation of spawning gravels in two streams on the Queen Charlotte Islands. In many respects these are representative of the small, coastal watersheds of British Columbia.

An oversized McNeil sampler was used to collect representative subsurface samples at 29 spawning sites. Surface material was characterized at 35 sites using Wolman counts, and an expedient photographic technique provided limited surface information at 116 sites. Detailed sediment sampling, magnetic tracer stones, and scour chains were used to study the impact of log jams on grain size.

Strong hillslope-channel interactions and an abundance of large organic debris preclude the development of simple grain-size trends. Two fisheries indices of gravel texture, the Fredle Index and percent finer than 3.36 mm (64.0 mm truncation), do not differ significantly between spawning sites. In contrast, surface median size and percent finer than 0.85 mm (64.0 mm truncation) differ significantly and stochastically between sites.

A sampling strategy, which aims to establish the general fisheries value of the bed material in a given stream, is then proposed. Number of samples, site selection, sample size, and mode of collection are specified in view of practical field considerations. This is regarded as an improvement on existing sampling methodologies. An issue of pressing concern, and one which hinders the development of effective field sampling, is the poor understanding of the relationships among fish survival, gravel quality indices, and sample truncation limits.

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1 INTRODUCTION

1.1 Background, Aims, and Uses

The size distribution of sediments in the bed of a stream channel (bed material texture) is a significant characteristic of fish habitat. Substrate permeability, hydraulic characteristics, and the abundance and diversity of the microinvertebrate benthic community, are dependent upon the grain sizes present and their relative proportions (McNeil and Ahnell 1964; NCASI 1986; Chapman 1988). Bed material texture is rated during habitat assessments and monitored in association with forest harvesting activities and habitat enhancement projects (Everest et al. 1987). For these reasons, understanding how and why bed material texture varies within British Columbia's coastal streams is important.

Several studies have noted the spatial variation of bed material texture at a variety of scales in the Pacific Northwest (e.g., Adams and Beschta 1980; Duncan and Ward 1985; Tripp and Poulin 1986), but the sampling criteria used in these studies are not generally consistent with accepted sedimentological gravel-sampling guidelines (e.g., Church et al. 1987). In particular, sample size is often too small for representative sampling of bed material, both at individual sites and within whole streams. This is indicative of widespread sediment sampling and analysis inconsistencies in the fisheries literature, as reviewed by Kondolf and Wolman (1993). Fisheries biologists need to decide upon criteria for assessing gravel quality (cf. Chapman 1988) and to standardize sample collection, analysis, and presentation procedures, both at individual sites and within stream basins. However, as long as the nature and causes of textural variation in stream channels remain vague, little progress can be made toward establishing such criteria.

A systematic program of within-creek bed material sampling, based on sound sedimentological criteria, has not been attempted in the small, steep, forested basins common in British Columbia's coastal mountain ranges. The identification of any systematic pattern in grain-size variations would introduce a predictive capability that would greatly simplify habitat assessment. Identifying the nature of variation would enable sampling for inventory or monitoring purposes to be conducted with greater validity. Everest et al. (1987) point out that high variability precludes attempts to instigate monitoring programs within creeks. By improving understanding of the system, unexplained variability is reduced and, in turn, it is easier to formulate sampling schemes that minimize confounding effects.

This study documents and attempts to explain spatial variations in bed material texture in two creeks on the Queen Charlotte Islands. Particular attention is given to spawning sites and how texture varies between such sites along the stream. This information is used to develop general sampling criteria for characterizing spawning gravel texture in similar channels.

1.2 Initial Ideas

Most observations of grain-size variation have been made in large river systems where the channel is protected from colluvial inputs by a buffering alluvial floodplain. Such channels can be described as "uncoupled" in that there is relatively little interaction with nearby

hillslopes. In the channel, sediment is transferred freely between alluvial bars that are spaced in response to prevailing hydraulic and sedimentological conditions. Uninterrupted fluvial abrasion and sorting processes result in a systematic, exponential decline in grain size with distance downstream.

In contrast, a channel can be described as "coupled" when material is transferred directly from the adjacent hillslopes to the channel by creep and episodic mass movement processes. Sediment transfers within coupled channels tend to be influenced by non-alluvial stream banks and in-channel obstructions such as large organic debris (Lisle 1986, 1987). Church (1983) used degrees of such hillslope–channel coupling to define landscape units suitable for the study of geomorphological processes on the Queen Charlotte Islands.

The distinction between coupled and uncoupled systems is fundamental for understanding grain-size variations at the drainage basin scale (Rice 1994). In coupled systems, stream channels receive fresh colluvial material along their entire length. These inputs consist of a wide range of grain sizes, including abundant fines, and are generally poorly sorted. In addition, in-channel obstructions are effective at sorting material.

Land-use history may alter the magnitude and frequency of mass movement events (Schwab 1983; Rood 1984) and the size and in-stream arrangement of large organic debris (LOD: logs, limbs, and root-boles >10 cm in diameter) (Hogan 1986). Consequently, it may also affect the variability of bed material texture.

The small (<50 km^2) steep, forested basins under consideration in the Queen Charlotte Islands are typical of many in the Coast Mountains. In some cases, strong coupling is evident along the entire length of the stream, from the headwaters to the ocean. In other instances, a valley flat is evident in the downstream portion of the basin, but coupling still dominates in the headwaters. Consequently the existing model of textural variation, developed from work carried out in uncoupled systems, is inapplicable (see Rice 1990 pp 6–13 for a review). In particular, it is hypothesized that hillslope inputs and special storage elements, such as large organic debris, preclude the development of any systematic variation in bed material texture.

1.3 Objectives

The main objective of this study is to obtain a better understanding of spawning-gravel texture variations in small channels on the Queen Charlotte Islands. This report will:

1. document the bed material texture of spawning sites;
2. (a) assess the hypothesis that systematic grain-size is precluded in the basins of interest, and
   (b) attempt to identify alternative patterns or trends (structure) and an explanatory model of textural variation;
3. assess the role of land-use history in affecting the variability of bed material texture; and, in turn
4. develop effective criteria for routine sampling and characterization of spawning-site sediments within small, steep coastal basins.

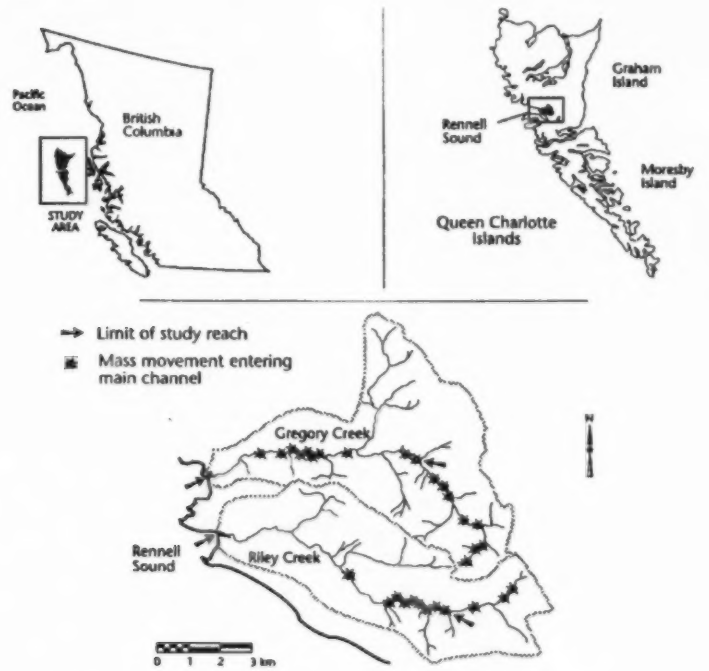
2 STUDY AREA AND METHODOLOGY

2.1 Study Area

Surveys of surface and subsurface bed sediments were conducted in Riley Creek and Gregory Creek, adjacent streams that drain into Rennell Sound (Figure 1). Drainage-basin characteristics are given in Table 1. In many respects the basins are similar (e.g., soft volcanic bedrock, high annual precipitation, high density of slope failures), such that the nature of geomorphic activity and the textural composition of weathered materials are expected to be similar.

This provides the basis for assessing the effect of contrasting land-use histories on textural variation (Objective 3). Harvesting in Riley Creek ceased in 1978 after 14% of the basin area had been clearcut. Harvesting in Gregory Creek ceased in 1980 after 2% of the basin area had been clearcut. The logged proportion of the actual study area is substantially greater in Riley Creek.

The entire length of Gregory Creek and the upper part of Riley Creek are strongly coupled. A valley flat in the lower reaches of Riley Creek protects it from hillslope failure. Of the eleven major slope failures (>1.0 ha) that impact directly on the main channel, none occurs within approximately 6 km of the mouth (Figure 1) (Jim Schwab, B.C. Min. For., pers. comm.). This provides an opportunity to assess the possible influence of a buffering valley flat on textural variation. Both creeks contain abundant LOD pieces and accumulations of LOD (accumulations of LOD are log jams) (Hogan 1986).



Location map of study area.

TABLE 1 *Study basin characteristics*

Characteristic	Riley Creek	Gregory Creek
Biogeoclimatic zone	CWH[a]	CWH[a]
Mean annual precipitation (mm)	>3600	>3600
Drainage basin area (km^2)	28.3	35.5
Relative relief (m)	840	840
Mainstem channel length (km^2)	10.6	11.0
Geology[c]		
Major formation	Yakoun	Masset
Minor formation	Masset	
Percent steepland area (>20 deg.)	39	41
Density of slope failures (no. km^{-2})		
All failures > 0.02 ha[d]	3.6	2.9
Failures entering creek >1.0 ha	0.6	0.4
Mean volume of incident failures (m^3)	5250	3350
Percent valley flat area (<2 deg.)	23	11
Logged area (%)	14	2
Harvesting ceased	1978	1980

a Coastal Western Hemlock
b blue line on 1:50 000 NTS
All data from Hogan (1989) except:
c from Sutherland Brown (1968): Yakoun soft volcanics (*pyroclastics, volcanic sandstones*); Masset soft volcanics (*pyroclastics,basalts*)
d from Rood (1984)

2.2 Sampling Overview

The variations of bed material texture in spawning areas along the lower 9.6 km of Riley Creek and 6.8 km of Gregory Creek were studied in an initial survey during the summer of 1989. These distances represent 90% and 65% of the mainstem lengths, respectively. Sites were selected along each creek independently of log-jam positions and colluvial sediment sources. The strength and form of the relationship between distance and grain size could then be assessed (Objective 2a). Sites were spaced fairly evenly between major confluences so that the influence of tributary sediment inputs could be assessed. Previous work indicates that confluences are often associated with discrete changes in bed material texture. At each site the actual sampling position was designated as the closest riffle-pool break, irrespective of local LOD and overbank inputs. This area is defined as the upstream portion of the riffle where the gradient begins to steepen and white water begins to appear. Riffle-pool breaks were sampled because this is where prime spawning gravels are found (Tripp and Poulin 1986). The consistent use of riffle-pool breaks throughout the sampling ensured that local scale variability was minimized. Site locations are shown in Figure 2.

On the basis of the ideas presented in Section 1.2, it was expected that the field program would have to identify a new explanatory factor of textural variation. This was confirmed by the surface samples of the initial survey, which could be analysed in the field, and by field observations, which suggested that LOD dominates textural variability. Hogan (1986, 1989) documented the geomorphological significance of debris pieces and jams, including their important sedimentological role.

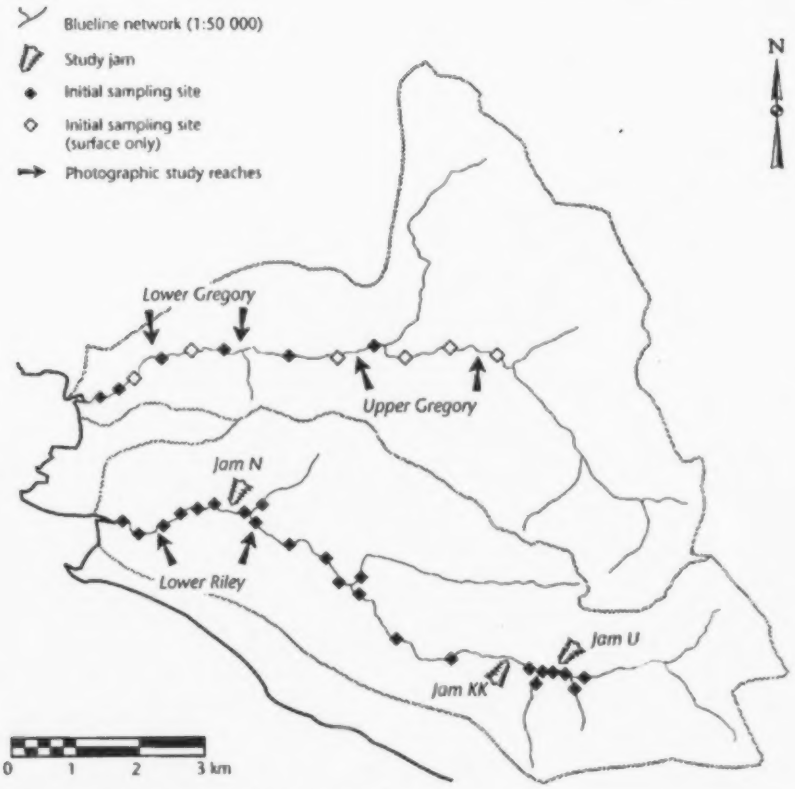


FIGURE 2 *Sampling sites and study jams.*

The initial survey used standard sedimentological techniques (Kellerhals and Bray 1971; Church et al. 1987) which provide complete and accurate information but are arduous and time consuming. The average frequency of the survey sites is two per kilometer. This resolution is too low for examining the effect of LOD, which occurs much more frequently (Hogan 1989). In order to obtain an appreciation of textural variation at a higher resolution (Objective 2b), two reaches in each creek were sampled during the summer of 1990 using a less rigorous photographic technique. This provided limited information about the surface materials at a large number of sites in a relatively short period of time. Although surface materials should not be used to infer anything about the quality of subsurface material (Section 4), sampling surface material is expeditious in investigating textural variability (Section 3.1). In addition to this high-resolution sampling, the LOD-effect was investigated by detailed examination of the textural variations around several log jams.

2.3 Initial Survey

At six sites in Gregory Creek and 23 sites in Riley Creek, a single bulk sample was taken using an oversized (205-mm diameter) McNeil sampler. This enabled the substrate in the active channel to be sampled to a depth of 25 cm with minimal loss of fines. NCASI (1986) found that the McNeil sampler provides the most precise method of sampling streambed gravels. Shovelling material from the creekbed invariably results in loss of fines, while freeze-core techniques are biased toward coarse particles that adhere to the periphery. The oversized sampler extends the range of sizes that can be sampled without bias, and minimizes the number of operations needed to obtain a representative sample.

A sediment sample must contain sufficient material such that each size class present in the sample is represented in its true population proportion. Church et al. (1987) found that in order to obtain a good estimate of the proportion of a size class, approximately 100 particles are needed. Fewer particles than this results in a significant variation in the estimated proportions between replicate samples of the same material. Since large particles are least frequent, a criterion based on the size of the largest particle present is sensible. Any individual clast in the largest size class present in the sample should not exceed 0.1% of the total sample weight (Church et al. 1987). In order that the total sample weight was not impractically large, a more relaxed 0.5% criterion was used in this study. This criterion can be regarded as the limit of representative sampling at isolated sites, where one is forced to sample gravels as large as 64 mm by hand. The 0.5% criterion is not ideal from a sedimentological point of view, but it is the most pragmatic approach, and is not expected to unduly influence the results and recommendations of this study.

Truncation of the subsurface sample at the coarse end is inherent in two of the commonly employed sampling techniques (freeze-core and McNeil) and, in any case, is necessary if any of the spawning-quality criteria currently in use are to be comparable between samples. For example, if a proportional value, such as the percentage finer than 0.85 mm, is to be transferrable, it must be expressed relative to some common range of sizes. In this study samples were truncated at 64 mm. Given the 0.5% criterion, a dry sample of 70 kg is required, and wet samples of 80 to 90 kg were therefore obtained. Up to six oversized-McNeil "pulls" of approximately 15 kg each were made across the riffle top. These were pooled to provide the full sample.

Replicate samples confirmed the value of the method used throughout the bulk sampling program. The pooled-McNeil method overcomes lateral heterogeneity caused by cross-section topography, and ensures that losses of fine material are minimized. A single sample taken from some point is unlikely to be representative of the entire unit. As long as cross-section morphology is similar, the downstream positioning of the sampling row, within the riffle-pool break, is not crucial (Rice 1990 pp 33–40).

In the field, a set of rocker sieves was used to sort the material finer than 64 mm into half-phi classes. The phi scale is commonly employed by sedimentologists, and is related to the mm scale as follows:

$$D_{phi} = -\log_2(D_{mm})$$

This logarithmic scale simplifies the presentation and mathematical manipulation of grain-size distributions that cover several orders of magnitude, and are often lognormally distributed. At the end of the sieving procedure, material finer than 16 mm, water from the McNeil pulls, and any additional water used during sieving was left to settle for a minimum of 16 hours. This was sufficient time for the suspended fines to settle. Free water was siphoned and carefully decanted, the damp material weighed, and a split of approximately 10 kg (wet) was obtained. In the laboratory a sample splitter was used to obtain approximately 5.0 kg (dry) for analysis. This split was dry-sieved using standard procedures through half-phi intervals to 0.063 mm.

At each bulk-sample site, and at an additional six sites in Gregory Creek, a surface sample of 100 stones was taken. A fibre tape was used to delineate one or more transects across the riffle top and stones were selected at regular intervals along the tape (the Wolman method). It has generally been found that stones finer than 8 mm in diameter are under-represented in such samples, and clasts smaller than 8 mm were therefore ignored. For each stone the three principle axes were measured. The intermediate axis (b-axis) is generally used as the representative measure of a grain's diameter, and that convention is followed throughout this study.

2.4 Replicate Samples

A knowledge of within-site variance is crucial if between-site comparisons are to be meaningful; that is, if between-site variance is to be confidently assigned to something other than sampling chance. Replicate bulk samples were therefore collected at two sites in Gregory Creek, and are used in Section 4.2 to calculate within-site variance estimates for various subsurface parameters. They were also used to investigate how and where bulk samples should be collected within each riffle-pool break.

A within-site variance term for surface material was also estimated. It has been recommended that a consistent estimate of average size requires at least 50 stones (Bray 1972). By randomly dividing the 100-stone sample from a single site in half, two representative replicate samples are obtained. This was done for eight randomly selected sites. For each 50-stone replicate the median grain size was determined, and for each pair the difference of the estimates calculated. These can then be used to provide an estimate of within-site variance of median estimates (Table 2). As field assessments of within-site homogeneity suggested, the variability of surface material within a single riffle-pool break is very small.

TABLE 2 *Initial survey surface material, within-site variance of eight pairs of replicate means*

	Surface D_{50} (mm)	phi
Mean differences	3.69	0.12
Replications	8	8
Mean standard error	1.83	0.06
Confidence limits[a]	4.33	0.14

[a] Confidence limits are for α=0.05

2.5 High Resolution Photographic Surveys

The surface sediments of two reaches in each creek (Figure 2) were studied using a photographic technique. This method is based on establishing an empirical relationship between median grain size and the number of particles in a given area on the bed surface (Church et al. 1987).

To establish the relationship, a standard area, delineated by a quadrat placed on the surface, is photographed at each site. The number of particles within the quadrat can be counted on the photograph. At a selection of the photographed sites, the median grain size of the exposed material within the quadrat is determined by direct measurement of a 100-particle sample. These "calibration" samples are used to define the relationship between grain size and number of particles. By counting the number of stones in the corresponding photo, this curve can be used to estimate the grain size at any site.

Within each of the photo reaches every riffle-pool break was photographed. In order to construct the calibration curve, median grain size was determined at 14 of the 116 sites photographed. These were distributed between the four reaches and were chosen to provide a wide range of grain sizes. The untransformed data from the 14 sites (Appendix 1) produce a significant relationship, but it was found that higher predictive power is attained if both variables are log transformed. The curvilinear relationship shown in Figure 3, fitted by eye, has the highest coefficient of determination ($r^2 = 0.924$) and lowest standard error of any of several relationships tried. The calibration was used to estimate the median grain size for each of the 116 photographed sites.

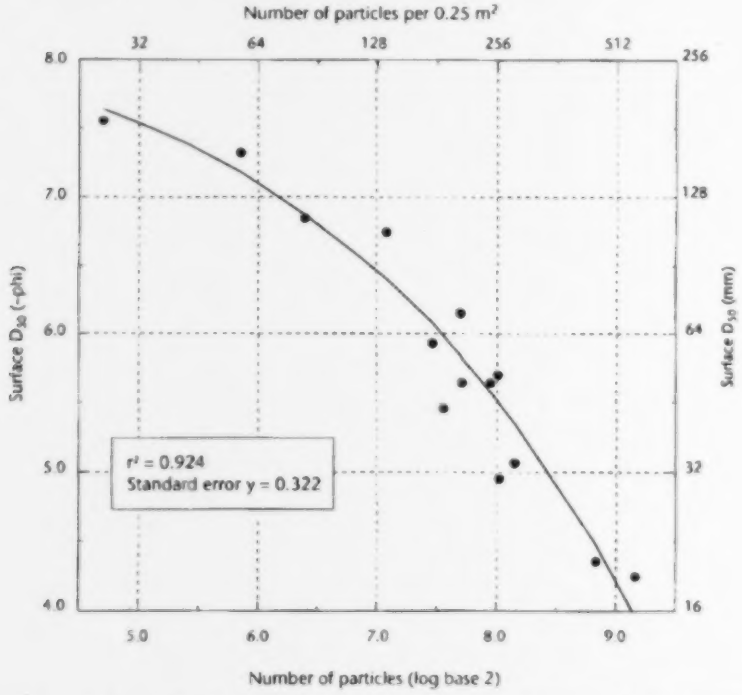


FIGURE 3 *Photo calibration curve for the relationship between median grain size and number of particles. Standard error is in phi units.*

2.6 Log Jam Studies

Field observations suggest that log jams and pieces of LOD can cause significant local sorting by altering channel gradient and presenting a physical barrier to mobile sediment. These observations are supported by data on the variation of D_{50} in surveyed creeks (Hogan 1989). In some cases surface texture is obviously different upstream and downstream of log jams. In other cases the distinction between upstream and downstream is less apparent. It is supposed that this reflects differences in sediment transport rate through the jam. This "permeability" is a function of various jam characteristics related to age and morphology. In this study, jam characteristics were classified according to the scheme of Hogan (1989). (See Appendix 6.)

In order to investigate these issues, three jams in Riley Creek were considered in detail (Figure 2). They were selected on the basis of their different ages and morphologies. Surface and subsurface samples were taken upstream and downstream of each jam according to a method suggested by Wolcott and Church (1991) and described in detail in Rice (1990).

In order to assess the relative sediment transport rates through the three jams (jam permeability), two complementary methods were used. Above each jam the creek was seeded with magnetic tracer particles. These fibreglass "stones" contain a small ceramic magnet and can be traced, even when buried, using a magnetic field locater (see Hassan et al. 1984 for discussion). By monitoring the transfer of these stones from the upstream to the downstream side of the jam over a winter season, a measure of each jam's permeability can be obtained. However, in order to make comparisons between the three jams some attempt must be made to normalize each rate relative to the ambient transport rate for the local reach. This transport rate was determined by observing the movement of separate batches of "stones" (of a different colour) deployed beyond any morphological evidence of jam influence.

As an adjunct to the stone placements, scour chains were positioned around jams U and N to assess relative aggradation and degradation. In each case four chains were placed at sites chosen because they appeared to be susceptible to net erosion or deposition. The scour chains and the inserter used were similar to those of Tripp and Poulin (1986). From the observations made upon return in the summer of 1990, maximum scour and fill and the net change in bed elevation at each site were calculated.

3 VARIATIONS IN SPAWNING GRAVEL CHARACTERISTICS

3.1 Systematic Variations

The knowledge that grain size varies systematically in a downstream direction is valuable in terms of the predictive capabilities that it brings. It is therefore important to assess the hypothesis, introduced in Section 1.2, that grain size does not vary systematically in strongly coupled streams.

While variations of subsurface material are of most interest in the context of spawning habitat, it is expedient to initially consider the surface material. Fluvial gravels are well known for their heterogeneity. At any site the material making up the entire bed will contain all sizes below some

upper limit determined by sorting and abrasion. However, there is a tendency for fine particles to be removed from the surface layer of the bed. Horizontal winnowing and vertical infiltration lead to the surface exposure of only the coarser particles at a site. The surface material is therefore a more critical indicator of downstream change, because the distribution average is not attenuated by ubiquitous interstitial fines. If systematic changes are not found in the surface data, then one can judge that the subsurface material is unlikely to vary systematically.

For each initial survey site the median grain size of the surface sample is presented in Appendix 2. These data are plotted in phi units against distance upstream in Figure 4. Phi units are used in order to simplify the identification of any exponential trends. Major tributaries are also marked on the plot. Previous studies have shown that if any trends are apparent they will be disrupted at confluences, such that systematic changes would only be anticipated in the intervening reaches (see Rice 1990 for review). The within-site variance estimate of the surface material, determined in Section 2.3, was used to assign 95% confidence limits to the median values of the surface samples (Figure 4).

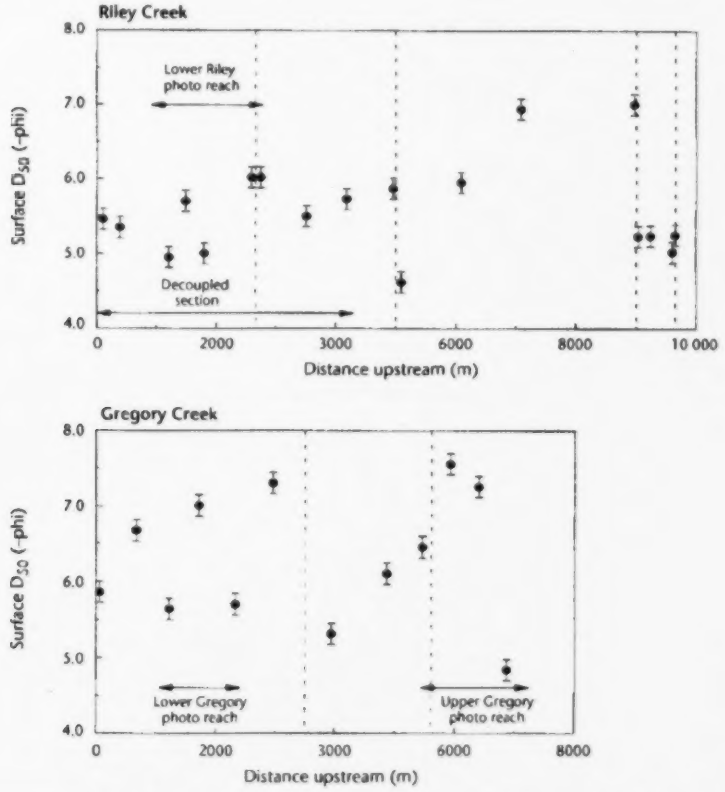


FIGURE 4 *Initial survey surface D_{50}. Replications provide an estimate of within-site variance. Error bars (α=0.05) are shown. Distances are from the ocean. Dashed lines indicate tributary entry points.*

Details of the analysis of these data, including a formal analysis of surface material variations (ANOVA), can be found in Rice (1990). In summary, in only one case is a significant, systematic, clearly exponential downstream-trend observed. In some instances it is possible that the data reflect a perturbed signal, but in several others the data behave very erratically, and exhibit no clear trend. In one case material coarsens significantly downstream. Because of the ambiguity of these results it is difficult to make any general comments.

The higher resolution photographic-survey data provide a more detailed picture of surface grain-size variation over distances of up to 1.9 km. Surface median grain-size estimates for every riffle-pool break in the four photographed reaches are given in Appendix 3. The location of these reaches is indicated on Figure 4. In Figure 5, D_{50} is plotted against distance upstream, again in phi units. The 95% confidence limits based on the standard error of the calibration model and within-site variance are also shown. The upper reach in Riley Creek is not considered here because of its short length. It is apparent from Figure 5 that grain size varies considerably and erratically over very short distances. The graphical evidence is supported by significant statistical analysis (Rice 1990).

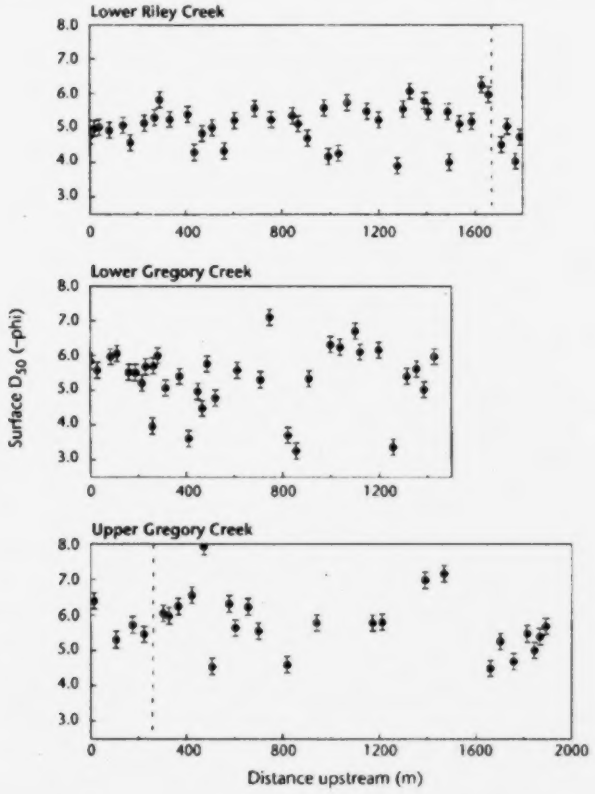


FIGURE 5 *Photographic survey surface D_{50}. A within-site variance estimate and confidence limits on the number -D_{50} calibration curve, provide an error bar (α=0.05).*

In conjunction with the initial survey data, this analysis confirmed that systematic changes in grain size are not apparent in these creeks. It is clear that distance downstream cannot be used to predict either the surface or subsurface texture of spawning gravels, as it can, at least to some extent, in larger uncoupled rivers.

3.2 The Effect of Log Jams on Bed Material Texture

In the streams studied, erratic fluctuations in grain size are visibly associated with large organic debris jams. Hogan (1989) documented this, and in a series of schematics, showed how highly variable local sediment-transport rates lead to variations in bed material texture. Further evidence in support of this conjecture is presented in this section.

3.2.1 *A Priori* ideas It is possible to suggest *a priori* how bed material texture should be affected in the vicinity of a log jam. In the most simple case, a log jam acts as a dam that is impermeable to sediment. This physical barrier leads to aggradation upstream and, in turn, local channel gradient is reduced. The entrapment of material prevents the resupply of the mobile fractions to the bed downstream and, supposing that size-selective transport is in operation, relative coarsening will occur. Upstream, the most mobile fractions will constitute the largest portion of the material being trapped and, consequently, relative fining will occur here (Figure 6). The ambient rate of sediment transport and the stability and longevity of the log jam may be important determinants of the absolute magnitude of the upstream/downstream contrast in grain size.

Log jams are temporally dynamic, commonly forming and disintegrating on timescales of up to 60 years in the Queen Charlotte Islands (Hogan 1989). An initially impermeable jam gradually becomes more permeable as it gets older. The integrity (strength) of the jam and the proportion of the channel width it occupies (span) decrease, while the number of channels that flow through it increase. In turn the upstream sediment accumulation is gradually released downstream and the upstream/downstream grain size disparity is moderated until it is no longer evident (Figure 6). Log jams are therefore expected to have a variable effect depending on their integrity, span and, in general, their age in so far as this affects permeability (Hogan 1989).

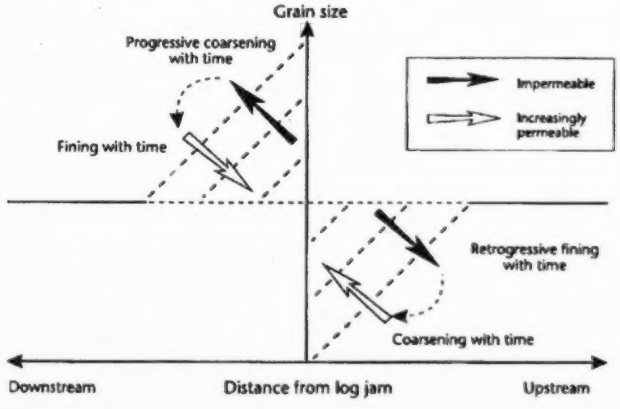


FIGURE 6 *Schematic of changes in sediment texture in the vicinity of a log jam.*

3.2.2 Study jams The relationships among log jam characteristics, sediment transfers, and grain size characteristics were examined at three log jams in Riley Creek. The jams were described in the field in terms of five characteristics which are thought to reflect jam permeability (Table 3). For each characteristic, semi-quantitative criteria were used to assign categorical values to the jam (see Appendix 6). In general, the higher the number, the greater the supposed permeability.

TABLE 3 *Study jam characteristics*

	Span	Integrity	Age	Channels	Sediment Storage
Jam N	2[a]	3	5	3	3
Jam KK	2	2	2	2	2
Jam U	1	1	2	2	1

Note: See Appendix 6, "Hogan's Jam Classification Scheme" for explanation of parameters.
[a] Jam is severely undercut

The three jams represent three levels of permeability. Jam U is an example of a highly impermeable jam. It spans the full channel width, is very strong, is breached by two relatively small channels, and is less than five years old. There is significant sediment storage upstream such that the channel is filled to the height of the jam (approximately 3 m) across the full bankfull width (approximately 10 m). This sediment wedge extends some 50 m upstream before grading back into the normal channel gradient.

In contrast, jam N is highly permeable. Although it spans three-quarters of the channel width, it is undercut by three channels, is of low integrity, and is between thirty and fifty years old. Upstream, the active channel is approximately 2.5 m below the uppermost bar surfaces close to the jam, suggesting active incision of a previous sediment accumulation. Jam KK is slightly older than jam U (although it belongs to the same age class), is weaker, and has lost more of its upstream sediment accumulation. It represents a condition somewhere between the high permeability of N and the low permeability of U, but is probably closer to U.

3.2.3 Confirmation of differential permeability Tracer particles were recovered at jams U and N. In both cases the movement of the green stones placed downstream of the jam indicates the ambient transport conditions. The movement of the orange stones placed upstream of the jam indicates the sediment transport through the jam. Movement distances and burial depths are given in Appendix 4, and particle displacements are shown graphically in Figure 7. Details of the recovery can be found in Rice (1990).

At both jams, green stones were recovered from the reach downstream of the deployment line (Figure 7). At jam N, a large proportion were found in a bar 90 m downstream of the line, and two were buried beneath 40 cm of gravel. This suggests a relatively active sediment transport regime at this site. At jam U, a greater proportion of the green stones remained close to their original positions, suggesting a less active bed, but some stones were found 90 m downstream.

At jam N, all but two of the orange stones had moved from their original positions. The rest were found spread along the reach as much as 190 m downstream of the jam. In contrast, none of the orange stones placed upstream of jam U was found downstream of the jam. All of the stones recovered were found in their original positions, buried by between 2 and 60 cm of gravel and sand.

Additional evidence of differential permeability comes from the scour chains. At jam U a chain was recovered intact from its position 15 m upstream of the jam. It recorded 8 cm of scour, followed by 30 cm of fill. This evidence, and the *in situ* burial of many of the tracer particles, reflects the aggradation at this site and, in turn, the low permeability of the jam.

At jam N three chains inserted immediately upstream of the jam were not found in 1990. Morphological changes suggest that they were scoured out completely. This upstream degradation reflects the increased permeability of the aging jam. Two chains were recovered from the downstream side of jam N. One recorded a net scour of 5 cm (which is only one or two particle diameters) and the other a net filling of 25 cm (47 cm of erosion and 72 cm of fill). This downstream aggradation is in keeping with the transfer of stored material through the jam.

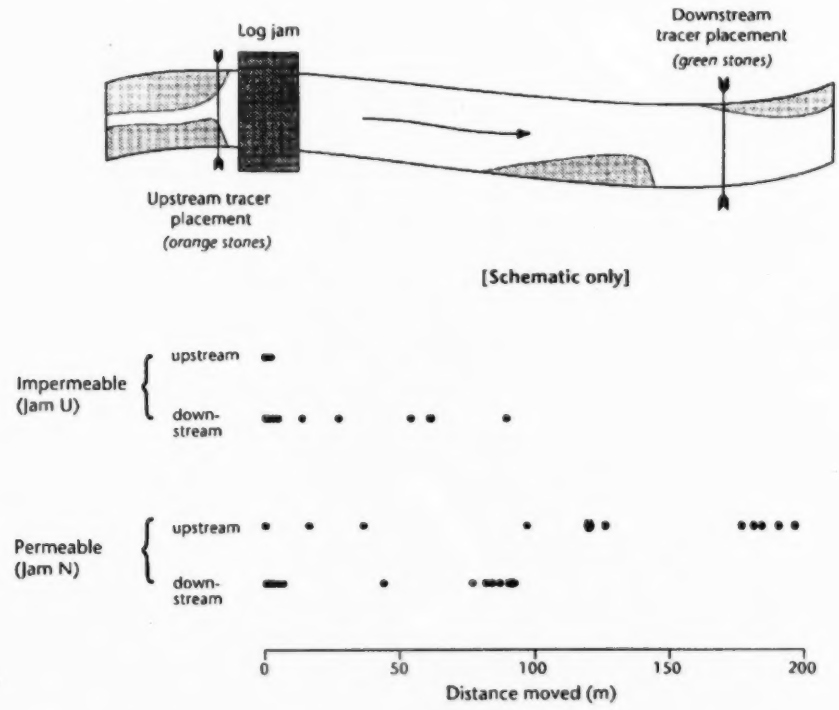


FIGURE 7 *Tracer stone displacements. Each circle represents one stone.*

In spite of the uncertainty regarding the whereabouts of unrecovered stones, the data available strongly suggest that jam N is relatively more permeable than jam U. The contrast of relative displacements upstream and downstream is striking and suggests that the transport rate through jam N is in keeping with local rates, but that the transport rate through jam U is significantly less than normal.

3.2.4 Bed material characteristics According to the *a priori* ideas above, the differences in sediment transport in the vicinity of these two jams should be reflected in the texture of the bed materials. The low permeability at U is expected to produce contrasting textures upstream and downstream, while the higher permeability at N should be associated with less textural differentiation. Surface and subsurface samples collected upstream and downstream of the three study jams support this argument, although statistical comparisons of the distributions are not possible because no replications were made.

Figure 8 shows the bed material texture at jams U and N. At jam U (and at jam KK) the downstream sediments are considerably coarser than those upstream. This is also apparent in survey photographs of the surface upstream and downstream of jam U (Figure 9), and in general views of jam KK upstream and downstream (Figure 10). In contrast, the surface distributions at jam N are very similar.

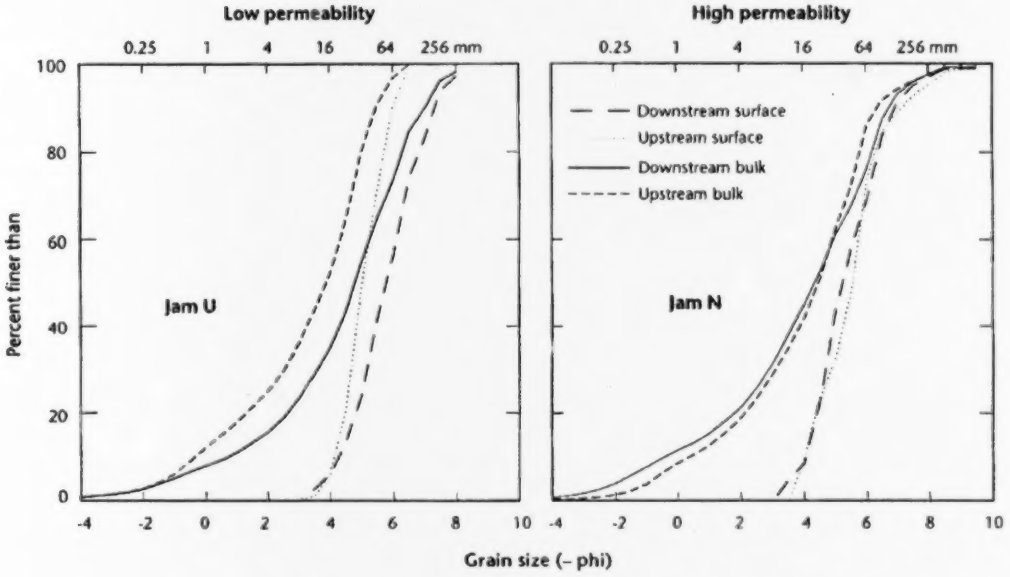
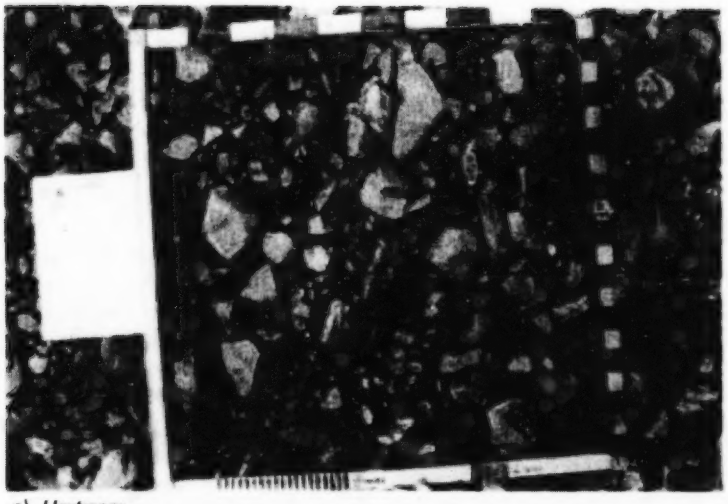
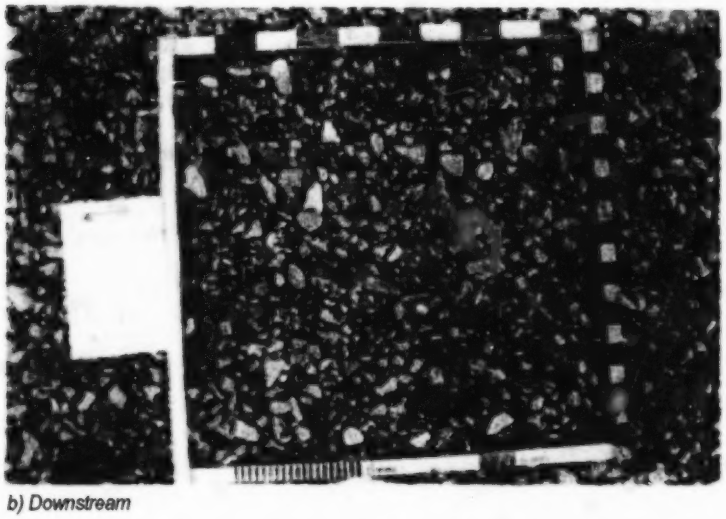


FIGURE 8 *Bed material texture in the vicinity of two log jams with differing sediment permeability characteristics.*



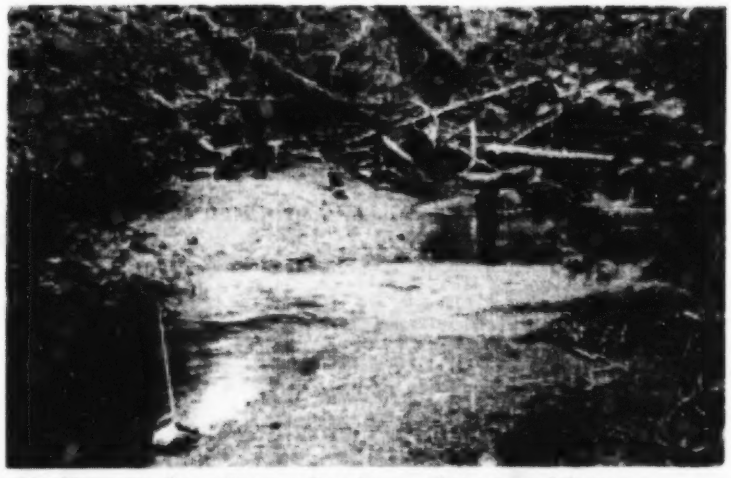
a) Upstream



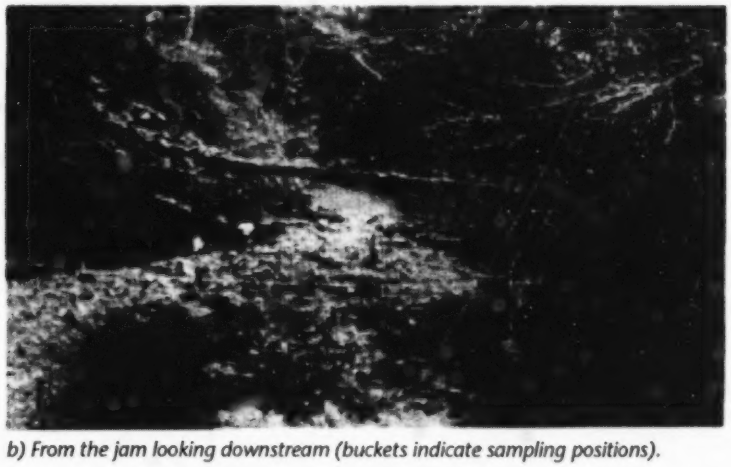
b) Downstream

FIGURE 9 *Survey photographs of the bed surface at Jam U, Upper Riley Creek.*

The subsurface material downstream of a jam is not expected to show great variability as a jam forms and disintegrates, since the progressive development of armour at the surface isolates it from the flow. However, upstream fining is expected, since the aggrading wedge is predominantly formed of the most mobile fractions of the bedload. Consequently, while an upstream and downstream difference in subsurface material is expected at impermeable jams, its magnitude is expected to be less than that of the surface difference. As with the surface material, the downstream transfer of the upstream sediment will moderate this difference as the jam ages.



a) Looking across the upstream sediment accumulation toward the jam.

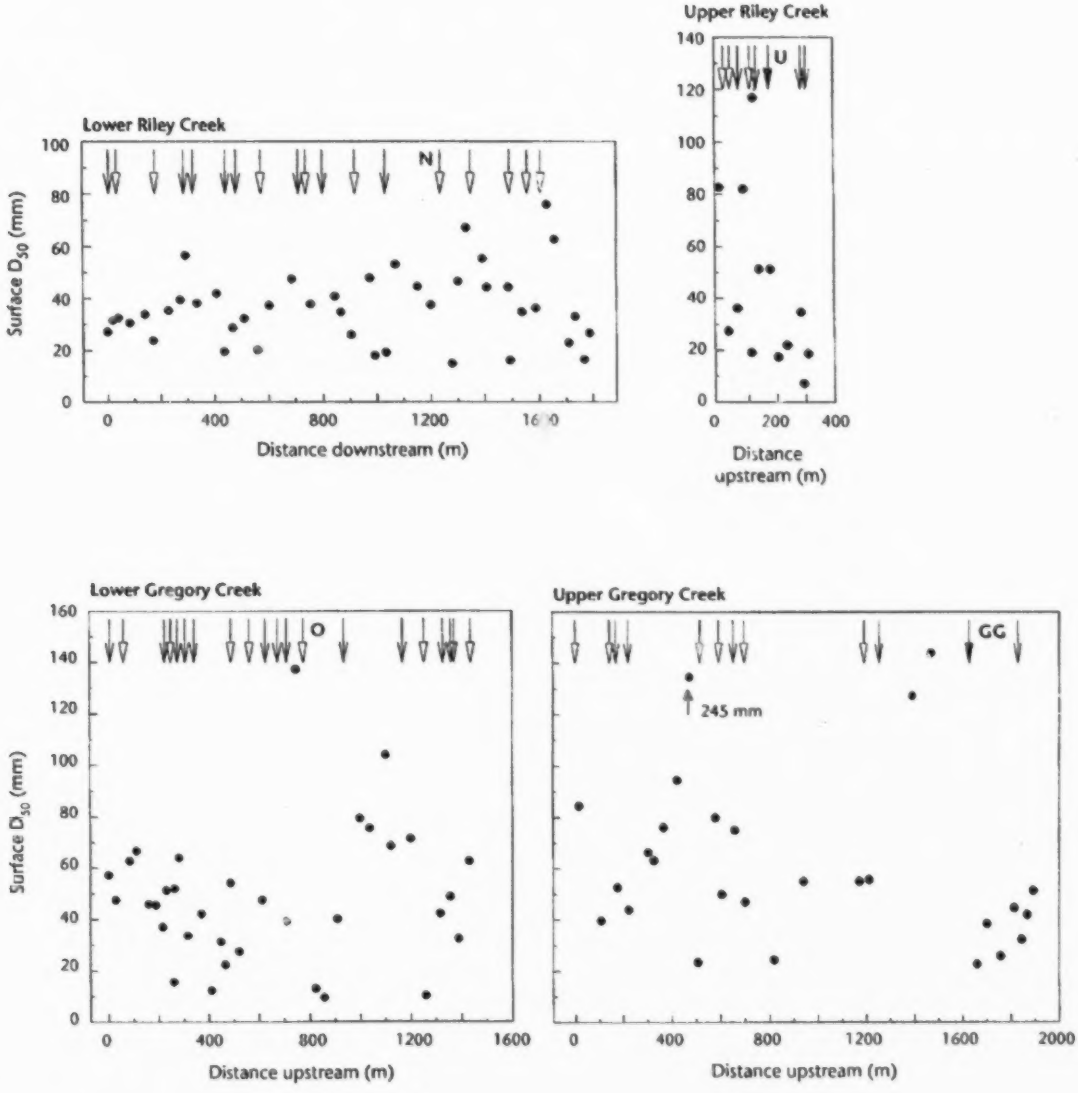


b) From the jam looking downstream (buckets indicate sampling positions).

FIGURE 10 *Sediments in vicinity of Jam KK, Upper Riley Creek*

Full subsurface distributions have been constructed (Rice 1990) and are shown in Figure 8. These distributions confirm the above expectations. At jam U the upstream material is finer than that downstream, but the magnitude of difference is not as large as at the surface (as indicated by the larger vertical difference between "percentage finer" for given grain size). In contrast, at jam N the sample distributions are very similar and the upstream and downstream subsurface materials are unlikely to be significantly different.

During the course of the photographic surveys, all the log jams encountered were characterized and their positions recorded. These data indicate the significance and abundance of LOD. In Figure 11, the surface D_{50} estimates (in mm) are plotted against distance for the four photographed reaches. Arrows along the top of each plot indicate the location of debris jams. The type of arrowhead indicates the permeability of each jam.



LEGEND

- Surface D_{50}
- Log jam, span + integrity ≤ 4, low permeability
- Log jam, span + integrity 5–7
- Log jam, span + integrity 8–10, high permeability

Surface grain size and log jams in the photographic survey reaches. Jams mentioned in text are indicated; type of arrowhead indicates the permeability of the jam.
a) Riley Creek photo reaches; b) Gregory Creek photo reaches.

Consider the highly impermeable jam GG at 1640 m in Upper Gregory Creek. This jam is approximately 7 m high and crosses the full channel width (15 m). A wedge approximately 200 m long has developed upstream and shows few signs of degradation (Figure 12a). Sediments in this wedge are fine and show some tendency toward coarsening upstream. In contrast, on the downstream side of the jam, surface material is very coarse for 200 to 300 m. The surface materials remain relatively coarse for at least another 800 m, except for a couple of finer sites at approximately 510 m and 820 m (Figure 11). In addition to the coarse texture, the volume of sediment in this reach is very low and sampling sites were difficult to find (Figure 12b). Large stretches of the creek are in bedrock and, in general, the reach is degraded as far as the tributary which enters the photo reach at 250 m (Figure 11).

a) Looking across the upstream sediment wedge toward the jam (indicated by prolific alder growth in the middle distance [note person for scale]).

b) Coarse surface texture approximately 900 m downstream of the jam (note people for scale).

FIGURE 12 *Sediments associated with Jam GG, Upper Gregory Creek.*

This is an extreme example of how a major jam can starve the downstream reach of sediment and produce severe changes in grain size and sediment storage. No other jams of this magnitude were found in either Riley or Gregory creek. Jam GG represents an end member of range of impacts that LOD can have. A more moderate effect occurs at jam O in Lower Gregory Creek where downstream coarsening over a much shorter distance is apparent. Two photos taken from a high bankside overlooking the jam (Figure 13) clearly show the fine upstream aggradation and coarse downstream degradation evident in Figure 11.

a) Looking from the left bank across sediment accumulation upstream of the jam, which is just to the left of the photo (open wedge is approximately 10 m wide).

b) Looking from the left bank toward degraded bed immediately downstream of the jam (indicated by overlying windthrow at bottom right).

FIGURE 13 *Sediment in the vicinity of Jam O, Lower Gregory Creek.*

In summary, individual log jams can, depending on their permeability, have a significant impact on local sediment texture. Furthermore, log jams are very common, occurring at a frequency of approximately 1 per 90 m in the photo reaches. They are undoubtedly the dominant cause of grain-size variation in these streams. In turn, a knowledge of jam location and characteristics may be the key to predicting textural variation.

3.2.5 Predicting grain size using log jam information This section examines whether any general relationships between surface grain size and jam proximity can be formulated. If so, then a knowledge of the positions and characteristics of the log jams within a creek would be the basis of a predictive model of grain-size variation between spawning sites. In accordance with the explanation of jam behaviour in Section 3.2.1, one expects to see the relationships shown in Figure 6 as permeability varies. The existence of such relationships was investigated in the following manner.

For each of the 60 log jams encountered in the photographically surveyed reaches, the distances from the upstream side of the jam to the closest sample upstream, and from the downstream side of the jam to the closest sample downstream were calculated. Number of channels, sediment storage, and a composite span and integrity index were used to stratify the data into permeability categories.

The expected outcomes are apparent in only a few cases and, in general, no trends are apparent (Rice 1990). There are several reasons for this:

1. There are very few young, impermeable jams, such as U and GG, in the two study creeks. These jams have the strongest impact on bed material texture.
2. Understanding of log jam behaviour is incomplete. It is possible that the variables used to categorize the permeability of the jams are not sufficiently sensitive to make useful distinctions.
3. The data are not of a sufficiently high frequency to be able to distinguish the upstream effect of one jam from the downstream effect of another. Consequently, many of the data are confounded by the upstream effect of log jams a short distance downstream, and vice versa.

One can identify several log jams that are isolated and therefore show clearly the relative grain-size variability expected, jam GG for example (Section 3.2.4), *but* there are not enough of these to permit the development of general grain-size:proximity relationships. One cannot therefore use information on log jams alone to predict grain size in these creeks.

3.3 Land Use and Valley Flats

The sampling recommendations presented in Section 6 depend upon a clear appreciation of the statistical variability of the spawning-bed sediments within the channel. Significant differences in variability could be caused by land-use history and the presence of a valley flat (Section 1). The differential land-use histories of Riley and Gregory creeks, and the valley flat in Lower Riley Creek (including the lower photo reach), provide an opportunity to determine whether or not this is the case. In order to maximize degrees of freedom and test efficiency, the photographic data (Appendix 3) were used in this analysis. A single exceptionally coarse outlier was removed from the Upper Gregory set. Summary statistics of

the surface D_{50} estimates in the four reaches are given in Table 4. The following conclusions were drawn on the basis of F-tests and t-tests with α=0.05.

Variance of the median surface grain size in the upper photo reach in Riley Creek is significantly greater than in the lower reach. Although the means are not significantly different, coupling has an effect on surface texture, and the two reaches must be considered separately. The absence of direct colluvial inputs in Lower Riley Creek reduces the absolute variability, but systematic trends are still precluded by LOD pieces and jams. In Gregory Creek, neither variance nor mean is significantly different between the two reaches.

The data from Upper Riley Creek are consistent with those in Gregory Creek. One can conclude that ten years after logging ceased, surface median grain size in spawning sites in Riley Creek is not significantly different from that in a relatively undisturbed watershed. The surface data for Lower Gregory, Upper Gregory, and Upper Riley creeks can then be regarded as a homogeneous set of data, which is distinguished from the surface material in Lower Riley Creek by its greater variability.

TABLE 4 *Characteristics of surface D_{50} in the photographic survey reaches*

Reach	n	Mean	Standard deviation	Variance
Upper Riley	12	43.9	32.16	1033.96
Lower Riley	42	36.6	14.03	196.98
Upper Gregory	26	58.2	29.08	892.90
Lower Gregory	34	48.6	26.74	714.85
Gregory (Upper + Lower)	60	52.7	28.31	801.23
Gregory + Upper Riley	73	51.2	28.99	840.34

3.4 An Alternative Predictive Model of Textural Variation

The surface D_{50} appears to behave stochastically; that is, to fluctuate randomly from one spawning site to another without any pattern or "structure." This has important implications for sampling strategies, and a general test of randomness was applied to clarify the issue.

The number of runs (an unbroken sequence of increasing or decreasing values) in a sequence of n data values can be used to test its randomness. A random process will tend to produce a number which is neither very large nor very small relative to the number of runs possible (n-1). A small number of runs indicates very little fluctuation and systematic behaviour (low-frequency structure). Conversely, a very high number of runs reflects oscillatory behaviour of a frequency similar to that of the sampling, and is similarly non-random (high-frequency structure). The "runs-up-and-down" test quantifies this analysis, and was applied to the initial survey and photographic survey data sets (Rice 1990).

The results showed that surface D_{50} varies randomly in all but one case, and suggest that a random model of grain-size variation is appropriate for these and similar streams. While there is no low-frequency structure in any of the data sets, there is evidence in Upper Gregory Creek of high-frequency structure close to the scale of bar-to-bar spacing.

Bar spacing is significantly greater in this reach than elsewhere because of the degradation associated with jam GG. This is reflected in the relatively low sampling density of this reach where one sample was collected every 2.8 bankful-widths (on average), compared with 1.2 in Lower Gregory Creek, 1.1 in Upper Riley Creek, and 1.1 in Lower Riley Creek. It is also notable that jam spacing is higher than elsewhere (6.1 bankful-widths, compared with 2.1, 1.3, and 2.4, respectively).

One possible explanation is that in the absence of much sediment, accumulations are largely restricted to log jams, which in turn produce the oscillatory signal. This is consistent with the frequency of jams being approximately half that of the sediment accumulations. Whatever the exact cause, it is perhaps wise to treat reaches which contain very large log jams as speci·' cases. Although the jam does not significantly affect the texture of the material present in the stream as a whole (texture in Upper and Lower Gregory creeks is not significantly different), it does seem to affect its arrangement within the channel. In any given stream along the mountainous coast of British Columbia, one or two such jams may not be unusual (Dan Hogan, B.C. Min. For. 1992, pers. comm.).

3.5 Summary

Systematic changes in spawning-site grain size are not evident within these creeks, and it is clear that LOD is largely responsible for the observed nature of textural variation. While isolated log jams affect sediment texture in a predictable way, their frequency, and the complexity of their effect, make it difficult to identify general relationships among jam characteristics, jam proximity, and sediment texture. Additional complexity is added by *numerous* non-alluvial sediment sources (gullies, debris torrents, bank erosion of glacial fill) which introduce fresh, unsorted material along the length of the stream. The degree of variability of surface texture appears to be more closely associated with hillslope-channel coupling than land-use history, at least ten years after disturbance.

It is reasonable to conclude that this complexity inhibits the development of a simple deterministic model of textural variation at the drainage basin scale. Observations show no pattern at this scale. Indeed, surface grain size varies randomly along most of the channel, and is best regarded as a random phenomenon for management purposes.

4 SUBSURFACE TEXTURE AND FISHERIES INDICES

In attempting to identify structure and relate it to causative factors, it was expedient to examine surface materials first. While surface texture is one aspect of fish habitat, the texture of the subsurface material as this affects gravel permeability is of major concern. An appreciation of the way in which subsurface texture varies between sites, and how much it varies between sites, is necessary before sampling recommendations can be formulated. On the basis of the results presented above, subsurface texture is unlikely to vary systematically; Rice (1990) provides additional direct evidence of this. In 'his section the outstanding issue of the magnitude of subsurface variations, particularly with regard to fisheries quality, is examined.

4.1 Fisheries Indices

Gravel permeability is determined by the full range of sizes present in the bed, and is indexed in several ways by fisheries biologists. Three indices used in previous studies on the Queen Charlotte Islands are considered here: percent finer than 3.36 mm; percent finer than 0.85 mm; and the Fredle Index (Tripp and Poulin 1986). The latter is regarded as a better index of substrate quality than percent fines measures because, by incorporating measures of both central tendency and spread, it relates more directly to permeability and porosity (Lotspeich and Everest 1981). The Fredle Index is the ratio formed by the geometric mean and the standard deviation of the truncated distribution:

$$FI = (d_1{}^{w}{}_1 * d_2{}^{w}{}_2 \ldots * d_n{}^{w}n)/(D_{75}/D_{25})^{0.5}$$

where d is the midpoint diameter of particles retained by a given sieve (mm), w is the fraction by weight of particles retained by a given sieve, D_{75} is the seventy-fifth percentile (mm), and D_{25} is the twenty-fifth percentile (mm).

All subsurface material indices must be applied to samples truncated at a common limit if between-sample comparisons are to be meaningful. The three indices were calculated using the initial field samples truncated at 64.0 mm. Percentages less than 0.85 mm and 3.36 mm, and the Fredle Index are given in Appendix 5, and are plotted against distance in Figure 14.

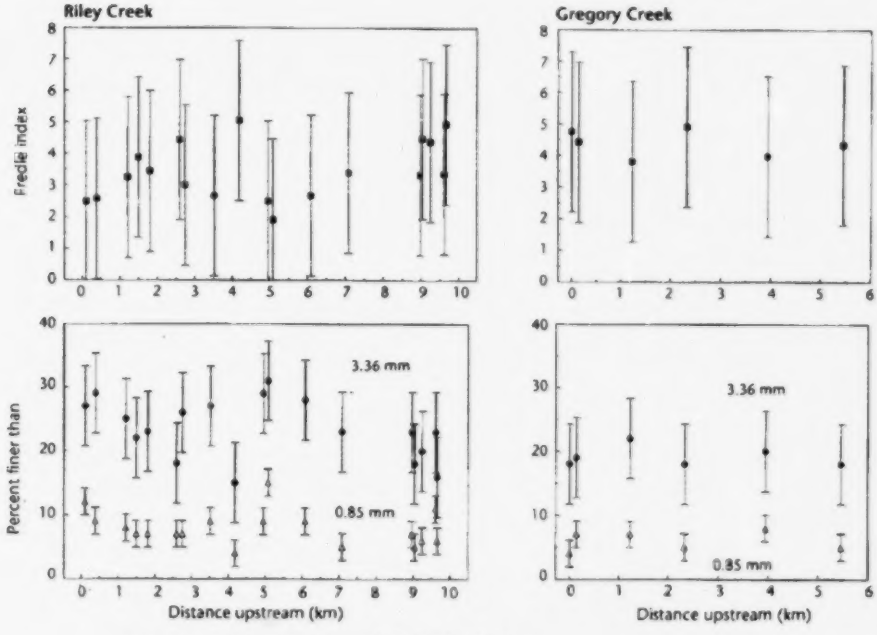


FIGURE 14 *Subsurface sample fisheries indices.*

4.2 Between-site Variation

To investigate whether the between-site differences can be associated with anything other than sampling chance, an estimate of within-site variance was calculated using replicate samples collected both in this study and during the 1983 FFIP (Fisheries/Forestry Interaction Program) synoptic

gravel survey. All of the samples are truncated at 64.0 mm, and were collected using McNeil samplers with appropriately large openings. For each sample the three fisheries indices are presented in Table 5.

TABLE 5 *Replicate subsurface samples, fisheries indices*

Sample	Fredle	%<3.36 mm	%<0.85 mm
REP	4.098	20.0	6.4
	4.349	18.3	5.8
	4.827	17.5	7.5
1A	5.748	15.2	6.4
	3.989	19.7	4.6
10A	4.604	19.4	4.3
	7.345	12.9	2.7
36A	3.704	21.2	5.0
	3.545	22.5	3.7
38D	4.286	19.7	5.5
	5.960	15.8	5.9
39A	3.657	22.2	5.5
	3.872	20.8	5.3
Pooled variance	1.15	7.05	0.78
95% confidence limit	2.54	6.28	2.09

Notes: Indices are for samples truncated at 64.0 mm.
REP collected in this study, others during FFIP synoptic gravel survey (1983).

The between-site variance terms were calculated for the entire set of initial survey samples (Table 6a). No differentiation between Riley and Gregory creeks, or between Upper and Lower Riley creeks was made at this stage, even though there are some grounds for expecting bulk composition to vary with land-use history and coupling. The between-site term therefore incorporates all possible sources of variation. If it does not differ significantly from within-site variance, then one can be confident that there is neither significant between-site variance nor any difference in variability due to coupling or land-use history.

Fredle indices show no significant difference between sites. Similarly the percentages less than 3.36 mm do not vary significantly between sites. However, the percentages finer than 0.85 mm show significant between-site differences at $\alpha = 0.05$ (and 0.01), and therefore require further investigation before sampling criteria can be specified.

It is important to point out that these results depend in part on the truncation limit chosen. Because of their nature, fisheries indices and relative between-site differences vary as a function of the truncation limit. The choice of truncation limits is discussed in some detail in Section 5.3.

As with the surface materials, there are two possible causes of significant variability in the percentage of material finer than 0.85 mm: coupling and land use. Those samples collected upstream of RLS 9 in Riley Creek are taken from the strongly coupled section, while those taken downstream of RLS 9 come from the valley-flat section. A comparison of

the percent less than 0.85 mm in the samples upstream of RLS 9 (inclusive) with that in the samples downstream of RLS 9 reveals that the existence of a valley flat does not produce a significant difference in either the variance or the mean (α=0.05).

TABLE 6 *Subsurface indices, between-site and within-site variation*

a) Riley and Gregory creeks undifferentiated

	Between-site variance	Within-site variance	F	$F_{(\alpha=0.05)}$
%<3.36	20.51(23)	7.05(7)	2.91	3.41
%<0.85	6.69(23)	0.78(7)	8.58	3.41
Fredle	0.83(23)	1.15(7)	0.72	3.41

b) Riley and Gregory creeks < 0.85 mm separately

	Between-site Variance	Within-site Variance	F	$F_{(\alpha=0.05)}$
Riley	7.37(17)	0.78(7)	9.42	3.48
Gregory	2.40(5)	0.78(7)	3.08	3.97

Note: Figures in brackets are degrees of freedom.

In Lower Riley Creek the frequency of jams is similar to that upstream, presumably because there is still an abundant supply of LOD and the channel is not large enough to prevent jam formation. These storage elements maintain the highly variable nature of the subsurface material despite the lack of hillslope inputs.

To assess the role of land use, the between-site and within-site variances of the percent less than 0.85 mm were compared for Riley and Gregory creeks independently (Table 6b). The between-site variances are not significant along Gregory Creek, but they are along Riley Creek. This suggests that logging leads to greater variability in the fines content of the subsurface material. However, confidence in such an inference is low because of the small number of observations in Gregory Creek and the lapse of ten years since logging in Riley Creek. More importantly, the results from Riley Creek show that percent less than 0.85 mm can vary significantly between spawning sites; a finding which is important for defining a robust sampling scheme. Given the more extensive nature of the Riley Creek data set it is sensible to accept, at least as a working generalization, that percent less than 0.85 mm varies significantly between sites. There is no evidence of systematic variation, and runs tests confirm that the index varies randomly along the channel.

4.3 Summary

For the Fredle Index and the percentage finer than 3.36 mm (64.0 mm truncation), within-creek, between-site differences are not significant, and there is no significant land-use or confinement effect. In other words, these indices do not show any significant variation between spawning sites, within these creeks. This is indicative of the isolation of subsurface materials and the role of LOD and strong coupling in preventing sorting and abrasion over long distances.

In contrast, the percentage finer than 0.85 mm (64.0 mm truncation) does differ significantly between spawning sites. As with the surface D_{50}, formal analysis reveals that the index varies stochastically.

5 GRAVEL SAMPLING RECOMMENDATIONS

Effective bed material sampling depends on understanding the nature of the variation in the textural parameters of interest. The preceding analysis has provided sufficient information to enable specification of a strategy for routine sampling of four commonly employed fisheries indices: Fredle Index; percent finer than 3.36 mm; percent finer than 0.85 mm; and surface D_{50}. After consideration of the sampling requirements of each parameter, a general strategy for sampling the spawning gravels of small, forested, coastal watersheds is outlined in Section 5.3.

It is important to point out that the hydraulically truncated coarse end of a grain-size distribution (seen on the surface), is useful for investigating spatial patterns, but that there is no simple relationship between the sizes visible on the surface and subsurface fisheries quality (Figure 15). Assessments of subsurface quality therefore require sampling of subsurface material. This makes walkthrough inspections unfeasible (Everest et al. 1981). It is unlikely that visual inspection of the surface layer, even by an experienced individual, can yield accurate assessments of subsurface quality.

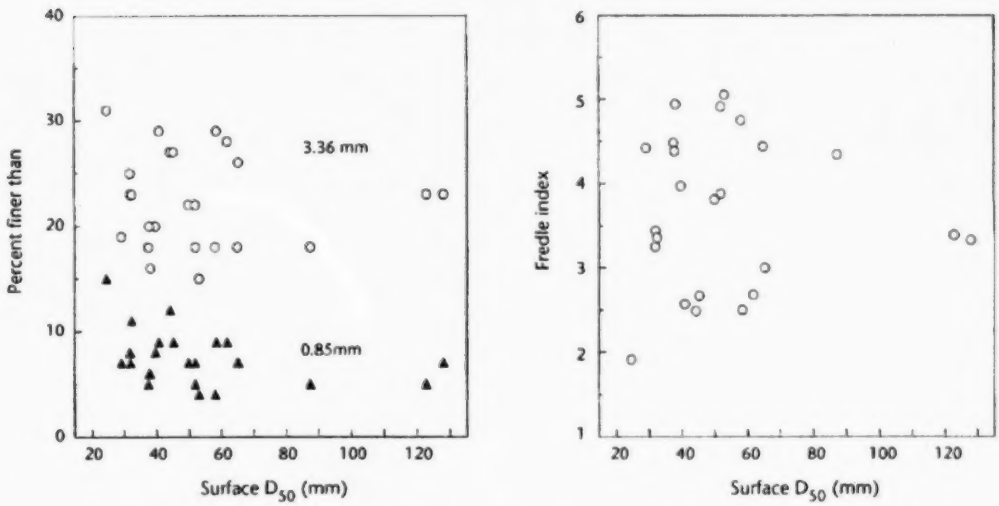


FIGURE 15 Surface D_{50} and subsurface fisheries indices.

5.1 Fredle Index and Percent Finer than 3.36 mm

Analysis suggests that variations between sites are not significantly larger than the variations one can expect to observe within individual riffle-pool breaks. Providing that replicate samples are collected, it is necessary to visit only one site in order to determine parameter mean and variance for the spawning gravels of the entire creek.

Analysis also suggests that a single replicate sample would be sufficient to characterize these indices in both of the creeks studied, despite differences in land use and coupling. However, it is important to realize

that there has not been active logging in these drainage basins for over ten years, and that bed texture may have recovered from any initial effect. Lithology, which was not a factor of concern in this study, may be a significant source of between-creek variation elsewhere.

5.2 Surface Median Size and Percent Finer than 0.85 mm

These parameters vary significantly but stochastically between sites. Relevant questions therefore concern sample size and sampling strategy. Given that the data are approximately normally distributed (Rice 1990), one can calculate the number of observations needed to obtain an estimate of the general population characteristics.

One assumes that the data in hand provide best estimates of the true population standard deviation (s) and mean (x) so that, given a specified level of precision (f) and a given confidence level t_n the number of observations needed (n) is given by,

$$n = [(t_n.s) / (f.x)]^2$$

With α=0.05, precision levels of 0.10 and 0.20 indicate that an estimate of the mean will be within 10 and 20% of the true population mean in 95 cases out of 100. The number of observations required to obtain these levels are given in Table 7. Coupling was shown to affect the variance of surface D_{50} (Section 3.3) and different sample sizes are specified accordingly. Coupling does not affect percent less than 0.85 mm, and no conclusions were reached regarding the influence of land use (Section 3.2). The subsurface data set from Riley Creek is the most extensive, and sample sizes for percent less than 0.85 mm are therefore specified using these data.

TABLE 7 *Recommended number of within-creek observations*

	No. of observations	
	20% precision	10% precision
Surface D_{50}		
a) Coupled (Upper Riley, Gregory and creeks)	30	120
b) Uncoupled (Lower Riley Creek)	16	60
Percent less than 0.85 mm		
a) Riley Creek	13	45

Note: Recommended number of observations calculated using sampling formula in Section 5.2 with α=0.08.

These precision levels have been chosen arbitrarily. For each index, some critical difference in value will exist that relates to a significant change in fish survival rates. It would be desirable to use a precision level that would distinguish such differences when defining sample sizes, but to my knowledge critical values have not been defined.

The required number of sampling sites can be arbitrarily positioned without sampling bias. That is, no stratification or particular spacing, other than that associated with pool-riffle spacing, is necessary to avoid biasing the sample.

Such a conclusion is of significant benefit to resource managers because the implication is that samples can be collected from any accessible riffle-pool breaks along the creek. On the basis of the present data this is the case, irrespective of land-use history and the situation of the channel with respect to hillslopes. In the latter case, individual log jams continue to cause significant variation despite a lack of slope inputs.

5.3 Routine Sampling Strategy

In general, the small, steep streams characteristic of much of British Columbia's coastline exhibit both strongly coupled and uncoupled reaches. Analysis has shown that in both situations, surface texture varies significantly and stochastically between spawning sites, but that the magnitude of the variability is less in uncoupled reaches. This has implications for the sample size required to characterize surface D_{50} (Table 7). For a typical coastal basin it is likely that a larger proportion of the channel system is coupled. More importantly, the delineation of coupled and uncoupled reaches may not be straightforward, especially in the field. To ensure adequate representation for a general case, sample size should be defined in terms of the coupled criteria.

The following is an outline, on the basis of present results, of the requirements for establishing the general fisheries quality of the bed material texture in a given creek.

Thirty surface samples and thirteen subsurface samples are needed to accurately characterize surface D_{50} and the 0.85 mm index (20% precision, 64.0 mm truncation of subsurface samples). Fredle Index and 3.36 mm indices may be calculated from the same samples, therefore, there is no need to collect a replicate sample at a single site to characterize these indices.

With the provision that rifle-pool breaks are consistently used, sample sites can be arbitrarily positioned at accessible points along the creek. One should recognize, however, that major jams, such as GG in Upper Gregory Creek, affect sediment texture over greater distances than more common jams, and may cause alterations in texture organization for many channel-widths upstream and downstream. It would be unwise to collect all of the samples in such reaches. Consequently, major jams should be identified either by air-photo analysis beforehand, or on the ground by recognizing a major aggradational surface upstream, or a lack of sediment, prevalence of bedrock, and relative absence of LOD downstream.

Each surface sample should consist of between 50 and 100 stones and should be collected using the Wolman or photographic technique. The need to define a calibration curve makes the latter only marginally more expeditious, and it is less informative than a Wolman sample. A McNeil sampler should be used to collect subsurface material once the surface layer has been cleared. Each subsurface sample should consist of material collected as a series of pooled grabs taken across the riffle perpendicular to the flow direction. This ensures that lateral variations do not introduce bias. With a 64.0-mm truncation, 70.0 kg of dry material gives a representative sample (Table 8). The McNeil sampler used should have a sampling tube diameter at least twice that of the truncation size.

This last point leads into the first of three important considerations that subsequent work should address.

In steepland streams with relatively coarse bed material, truncation makes portable sampling a practical possibility. Given the nature of fisheries indices it is, in any case, necessary if between-sample comparisons are to be meaningful. The physical dimensions of the McNeil sampler impose some upper limit for the truncation point (say at 90 mm for a 205-mm sample barrel). Within this constraint, the truncation point should be determined by the range of sizes over which habitat indices most usefully relate to fish survival.

TABLE 8 *Recommended sample sizes by mass (kg)*

Truncation size (mm)	Weight of largest clast in sample (kg) 1%	0.5%	0.1%
11			3
16		2	6
22	2	3	14
32	5	10	45
45	13	26	130
64	36	70	370
90	100	*190*	*1000*
128	*300*	*600*	*3000*
256	*2400*	*4600*	*+9999*

Note: From Church et al. (1987), who recommended the 0.1% criterion for representative sampling. The 0.5% criterion was used in this study, and is proposed as a practical alternative. Sample sizes beyond the limit for hand operations in isolated areas are indicated in italics. Masses given are for dry material.

Unfortunately this issue has received little attention, and the 64.0-mm truncation adopted here is somewhat arbitrary. If it were determined that a lower truncation point is as good, or better, for determining bed material indices that are sensitive to survival rates, then smaller sample sizes could be recommended (Table 8). If we wish to minimize field effort, it is imperative that the relationships among fish survival, gravel quality indices, and common truncation limits be given immediate attention.

Secondly, it is possible that land use and lithology have an effect on bed material texture and its variability within creeks on the Queen Charlotte Islands (Tripp and Poulin 1986). If so, sampling requirements would vary depending on the land-use history of the creek and its lithology. Such a large-scale structure would enable one to make basin-scale generalizations about textural variation on the basis of limited field effort. In this study the results regarding land-use history are inconclusive. A larger data set from an undisturbed basin and data from more recently disturbed basins than Riley Creek are needed in order to reach tenable conclusions.

Thirdly, given that one's intention in undertaking sampling is to establish the general characteristics of the bed material in an entire creek, an expedient method may involve pooling sample grabs as proposed by Wolcott and Church (1991). This technique was used in sampling bed material close to the study jams and is discussed by Rice (1990). It could

conceivably be used at the creek scale to maximize sampling efficiency. It would involve collecting only a portion of the required sample weight (subsurface) or number of stones (surface) at each of the arbitrarily positioned sites. These grabs would then be pooled to give a single representative sample. This is mentioned here as a potential way to minimize field effort, but it is not recommended prior to critical assessment.

6 CONCLUSIONS

Based on available literature, it is apparent that inadequate sampling methodology, inconsistent acquisition techniques, and incomplete data presentation, characterize many studies of spawning gravels. Insufficient sample size, both at individual sites and within a stream, and the lack of a standard truncation limit, are common problems. It is clear that a concerted effort is needed to decide upon criteria for assessing gravel quality (cf. Chapman 1988) and to standardize sample collection, analysis, and presentation procedures. This will be facilitated, at least in part, by studying the variation of spawning gravels within a variety of channels.

This study has examined the spatial variation of spawning gravel characteristics in two streams on the Queen Charlotte Islands. The general objectives were twofold: to develop an appreciation of the nature and causes of textural variability in small, coastal watersheds; and to establish criteria which allow routine, representative sampling of spawning gravels within such streams.

Surface and subsurface materials at a number of sites within each creek were sampled using several methods. Both median surface and subsurface grain size exhibit no systematic relationship with distance downstream and, in general, grain size fluctuates widely over very short distances. Detailed consideration of relative sediment transport rates and local bed material texture confirmed that, depending on permeability, individual log jams can cause significant variations in bed material texture. However, the high frequency and variable effect of log jams, and the strength of hillslope–channel coupling make it difficult to develop any general relationship between sediment characteristics and jam proximity.

Further analysis revealed that two fisheries indices, the Fredle index and the percent finer than 3.36 mm (64.0 mm truncation), do not differ significantly between spawning sites. In contrast, surface D_{50} and percent finer than 0.85 mm differ significantly and stochastically between spawning sites. Hillslope–channel coupling affects the magnitude of the variation in surface material texture. No conclusions were reached regarding the influence of land use on spawning gravel variability.

On the basis of these results a routine sampling strategy has been proposed. This aims to establish the general fisheries value of the bed material in a given creek. Number of samples, site selection, sample size, and mode of collection are specified in view of practical field considerations. Perhaps of most importance is the stochastic nature of significant within-creek variation, which suggests that sampling sites can be positioned arbitrarily without introducing bias.

Several issues require attention. First, effective field effort cannot be minimized until the relationships among fish survival, gravel quality indices, and common truncation limits are thoroughly examined. Second, it is possible that the pooling of sample grabs from individual sites can provide an expedient sampling method. Third, lithology and land use may introduce large-scale structure. This would require distinct sampling criteria for basins of different lithology and land use. The present study could be used as an exemplar to establish such criteria and, indeed, to identify sampling criteria in regions other than coastal British Columbia.

APPENDIX 1 PHOTOGRAPHIC SURVEY CALIBRATION DATA

Site	Number of stones >8 mm (0.25 m^{-2})	Surface material median (mm)
LR 292	209	50
LR 845	284	34
LR 975	246	50
LR 1331	176	61
LR 1658	188	44
LG 0	207	71
LG 189	260	31
LG 160	257	52
LG 466	456	21
LG 259	574	19
UG 15	135	107
UG 472	26	188
UG 1469	58	160
UR 194	84	115

APPENDIX 2 INITIAL SURVEY SURFACE D_{50}

Site	Distance upstream (m)	Surface D_{50} (mm)	Surface D_{50} (Phi)
RLS 1	105	44.3	-5.46
RLS 2	385	40.8	-5.35
RLS 4	1211	31.8	-4.95
RLS 5	1490	52.0	-5.70
RLS 6	1801	32.0	-5.00
T1 DS	2594	64.9	-6.02
T1 US	2746	65.3	-6.02
RLS 7	3514	45.3	-5.50
RLS 8	4186	53.1	-5.73
T2 DS	4954	58.5	-5.87
T2 US	5089	24.6	-4.62
RLS 9	6089	61.8	-5.95
RLS 10	7089	122.8	-6.94
T3 DS	8969	128.0	-7.00
T3 US	9034	37.5	-5.23
RLS 11	9241	37.8	-5.24
JWUS	9608	32.4	-5.02
T4 US	9656	38.1	-5.25
T1 TR	2650	33.6	-5.07
T2 TR	5000	75.1	-6.23
T3 TR	9000	57.3	-5.84
T4 TR	9656	34.5	-5.11
GLS 1	60	58.1	-5.86
REP	150	29.2	-4.87
GLS 2	680	102.5	-6.67
GLS 3	1230	49.9	-5.64
GLS 4	1720	128.0	-7.00
GLS 5	2330	52.0	-5.70
GLS 6	2961	157.6	-7.30
GLS 7	3942	39.7	-5.31
GLS 8	4870	68.6	-6.10
GLS 9	5455	87.4	-6.45
GLS 10	5925	187.4	-7.55
GLS 11	6395	152.2	-7.25
GLS 12	6865	28.6	-4.84

APPENDIX 3A PHOTOGRAPHIC SURVEY SURFACE D_{50} IN RILEY CREEK

Dist.(m)	Number	D_{50} (mm)	Dist. (m)	Number	D_{50} (mm)
Lower reach			Upper reach		
0	398	27.1	0	138	82.7
20	352	31.6	30	394	27.5
40	346	32.5	62	315	36.3
61	361	30.5	83	139	82.1
140	334	33.8	109	502	19.2
170	399	26.7	118	84	117.0
226	324	35.3	137	229	51.3
272	295	39.4	176	230	51.3
292	209	56.5	203	470	21.4
335	303	38.1	235	452	22.0
409	279	41.9	283	328	14.8
436	495	19.6	293	846	7.1
469	379	28.6	307	508	18.8
512	347	32.2			
560	488	20.1			
605	309	37.3			
684	248	47.5			
757	305	37.8			
845	284	40.8			
868	327	34.8			
906	406	26.0			
975	246	47.8			
992	523	18.0			
1034	501	19.2			
1070	224	53.1			
1151	262	44.6			
1201	306	37.5			
1278	567	14.9			
1302	252	46.5			
1331	176	67.2			
1392	214	55.3			
1407	263	44.3			
1467	263	44.3			
1492	559	16.1			
1537	327	34.8			
1588	315	36.3			
1629	153	76.1			
1658	188	62.7			
1710	449	22.8			
1755	367	33.1			
1768	556	16.3			
1769	401	26.5			

APPENDIX 3B PHOTOGRAPHIC SURVEY SURFACE D_{50} IN GREGORY CREEK

Dist. (m)	Number	D_{50} (mm)	Dist. (m)	Number	D_{50} (mm)
Lower reach			Upper reach		
0	207	57.3	15	135	84.5
29	248	47.5	107	293	39.7
84	187	62.7	176	225	52.7
111	177	66.7	223	265	44.0
160	257	45.9	303	178	66.3
189	260	45.6	327	186	63.1
216	309	37.0	366	153	76.1
230	231	51.3	423	116	94.3
259	547	15.6	472	26	245.6
263	226	52.0	507	441	23.4
281	184	64.0	579	145	79.9
315	336	33.6	605	235	49.9
371	275	42.2	658	155	75.1
410	655	12.2	700	251	46.9
440	354	31.3	818	429	24.3
466	456	22.3	940	216	55.0
487	219	54.1	1172	217	54.8
522	394	27.5	1211	213	55.7
611	245	47.5	1391	73	127.1
709	295	39.4	1469	58	144.0
747	63	137.2	1660	453	22.7
823	638	13.0	1702	303	38.3
857	745	9.5	1757	409	25.8
909	288	40.2	1815	261	44.6
998	146	79.3	1845	347	32.2
1037	154	75.6	1869	278	41.9
1099	101	104.0			
1893	229	51.3			
1120	173	68.6			
1198	164	71.5			
1258	712	10.3			
1315	276	42.2			
1355	241	48.8			
1387	344	32.5			
1429	187	62.7			

APPENDIX 4 TRACER STONE MOVEMENTS (1989–1990)

Jam U				Jam N			
Green		Orange		Green		Orange	
Dist.	Depth	Dist.	Depth	Dist.	Depth	Dist.	Depth
0.0	0.02	0.1	0.15	0.9	0.00	0.0	0.02
0.2	0.00	0.5	0.60	0.3	0.00	0.0	0.02
0.1	0.00	0.0	0.55	0.2	0.00	0.7	0.10
0.5	0.02	0.3	0.25	1.4	0.02	16.5	0.10
0.4	0.00	0.2	0.15	1.7	0.02	36.6	0.10
0.9	0.00	0.3	0.15	3.5	0.05	97.0	0.00
1.2	0.00	0.3	0.12	5.2	0.05	126.1	0.00
2.2	0.00	0.4	0.16	6.9	0.03	119.5	0.15
2.9	0.00	0.3	0.15	44.0	0.00	120.5	0.00
3.1	0.05	1.7	0.20	76.9	0.00	176.9	0.15
0.6	0.01	2.7	0.15	76.9	0.00	181.4	0.10
0.3	0.05	0.2	0.02	81.9	0.40	184.4	0.10
5.3	0.00			84.1	0.40	190.7	0.10
14.0	0.00			87.0	0.10	196.7	0.15
27.4	0.12			91.3	0.15		
54.2	0.02			92.4	0.01		
61.1	0.10			92.6	0.04		
89.4	0.10			90.0	0.05		
61.9	0.07						

Notes: All measurements are in metres.
Jam U: Jam is 6–12 m downstream of orange line.
Green line is 80 m downstream of orange line.
Jam N: Jam is 5–15 m downstream of orange line.
Green line is 96 m downstream of orange line.

APPENDIX 5 SUBSURFACE SAMPLE FISHERIES INDICES

Site	Distance upstream (m)	Surface D_{50} (mm)	Fredle Index	Percent finer than 3.36 mm	Percent finer than 0.85 mm
RLS 1	105	44.3	2.49	27	12
RLS 2	385	40.8	2.57	29	9
RLS 4	1211	31.8	3.25	25	8
RLS 5	1490	52.0	3.88	22	7
RLS 6	1801	32.0	3.44	23	7
T1 DS	2594	64.9	4.44	18	7
T1 US	2746	65.3	3.00	26	7
RLS 7	3514	45.3	2.67	27	9
RLS 8	4186	53.1	5.05	15	4
T2 DS	4954	58.5	2.50	29	9
T2 US	5089	24.6	1.91	31	15
RLS 9	6089	61.8	2.68	28	9
RLS 10	7089	122.8	3.39	23	5
T3 DS	8969	128.0	3.33	23	7
T3 US	9034	37.5	4.48	18	5
RLS 11	9241	37.8	4.38	20	6
T4 DS	9608	32.4	3.36	23	11
T4 US	9656	38.1	4.94	16	6
GLS 1	60	58.1	4.75	18	4
REP	150	29.2	4.42	19	7
GLS 3	1230	49.9	3.81	22	7
GLS 5	2330	52.0	4.91	18	5
GLS 7	3942	39.7	3.97	20	8
GLS 9	5455	87.4	4.34	18	5

Note: Bulk indices are for material truncated at 64 mm.

APPENDIX 6 HOGAN'S LOG JAM CLASSIFICATION SCHEME

This appendix is an abridged version of the classification scheme developed by Dan Hogan during his work on the Queen Charlotte Islands (Hogan 1989). A log jam is defined as a major accumulation of debris that alters, or has altered recently, sediment transport downstream and channel stability. Several log jam features that relate to the geomorphological functioning of log jams are included in the classification. In this study, log jams have been described in terms of five of the eight parameters identified in Hogan's (1989) classification. These are described below. For each parameter a ranking system from 1 to 5 is used to classify the jam in question. In general, lower rankings indicate impermeability and strength, while higher numbers are associated with the deterioration of the jam and increasing permeability.

Jam Feature Rank Characteristics

Jam age

1 Very young; new trees (bark, branches), no nursed trees, apparently formed during last major storm event (less than 2 years old).
2 Recent; LOD has some bark and branches, nurse trees (usually red alder) are less than 5 m high, less than 10 years old.
3 Moderate; nursed trees between 10 and 20 years old (aged by increment bores).
4 Moderate to old; nurse trees between 20 and 30 years old, LOD has few branches and no bark.
5 Old; debris is smooth except for moss, nursed trees are 30 to 50 years old.
5+ Very old; nursed trees are over 50 years.

Jam integrity

1 Very solid; large, well-anchored LOD pieces, no rot, compact structure.
2 Solid; smaller pieces, anchored, fairly compact.
3 Moderate; less compact, open spaces between LOD, some rot.
4 Weak; poorly structured individual pieces, poor anchoring, rot.
5 Very weak; small pieces, no anchoring.

Jam span (lateral extent)

1 Complete; jam completely crosses the channel and forms a dam over which water flows.
2 Incomplete; 3/4 < span < 1bankfull width.
3 1/2 < span < 3/4 bankfull width.
4 1/4 < span < 1/2 bankfull width.
5 Span < 1/4 bankfull width.

Sediment storage (upstream)

1 Full; the channel zone is completely full of sediment (i.e., sediment is level with the top of the jam, fills the bankfull width, and extends upstream as a function of channel gradient).
2 Not full; < 1/4 of sediment evacuated (cf. 1).
3 1/4 to 1/2 removed.
4 1/2 to 3/4 removed.
5 Empty; all sediment removed.

Number of channels

1 Single channel.
2 Two channels.
3 Three channels.
4 Four channels.
5 Five or more channels.

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